Effectiveness of geophysical surveys for water wells relocation in overexploited aquifers (the example of Maggiore and Traversola Valleys, Northwestern Italy)

Published version:

DOI:10.1007/s12665-017-7218-0

(Article begins on next page)

De Luca, D.A., Comina, C., Lasagna, M. et al. " Effectiveness of geophysical surveys for water wells relocation in overexploited aquifers (the example of Maggiore and Traversola Valleys, Northwestern Italy)" Environ Earth Sci (2018) 77: 19.

https://doi.org/10.1007/s12665-017-7218-0

Effectiveness of geophysical surveys for water wells relocation in overexploited aquifers (the example of Maggiore and Traversola Valleys, Northwestern Italy).

Domenico Antonio De Luca[1], Cesare Comina[1], Manuela Lasagna[1], Enrico DeStefanis[1], Luciano Masciocco[1], Alberto Godio[2] and Stefano Stocco[3]

[1]DST – Università degli Studi di Torino

[2]DIATI – Politecnico di Torino

[3]GAMUT S.r.l. - Spin off Company of Politecnico di Torino

Abstract

Aquifer overexploitation is a common problem in drinking water management. This will become more and more important given the general reduction of water resources. To overcome overexploitation, one of the most adopted solution is the relocation of extraction wells. To establish the positions of new wells, a precise knowledge of the hydrogeological setting is required. Specific surveys are therefore necessary to obtain information over wide investigation zones. Geophysical methods, particularly electromagnetic and electrical, can be useful with this aim. In the present paper a case history on the combined use of ERT (electrical Resistivity Tomography) and TDEM (Time Domain Electromagnetic) soundings is reported. Surveys have been performed within the Maggiore and Traversola Valleys, to investigate the uppermost part of the Quaternary deposits, hosting the near surface aquifer. The electromagnetic data have been inverted with a Spatially Constrained approach by assuming a quasi 1D model of the sub-surface. Geophysical surveys allowed for depicting the depth and lateral continuity of the supposed aquifer level in the surveyed area up to a depth of about 200 m and proposing potential positions for well relocation.

Key-words: Groundwater management, Overexploited aquifer, TDEM soundings, spatially constrained inversion, Electric Resistivity tomography.

1. Introduction

The well field of Maggiore and Traversola Valleys, located in the central part of Piedmont Region (northwestern Italy), plays a strategic role in supplying drinking water to the Asti and Monferrato hilly area. As this confined aquifer is the only source of water for human consumption in the area, the well field of Maggiore and Traversola Valleys is considered of regional importance. More than 40 wells (Figure 1), concentrated in a very limited area, provide drinking water to 43 municipalities within the Asti Province. The total amount of water withdrawn is approximately 16 Mm^3/year (i.e. a total pumping rate of about 530 l/s) (ATO5, 2015); about the 50 % of the total extracted water supplies the Asti City, with about 76.000 inhabitants.

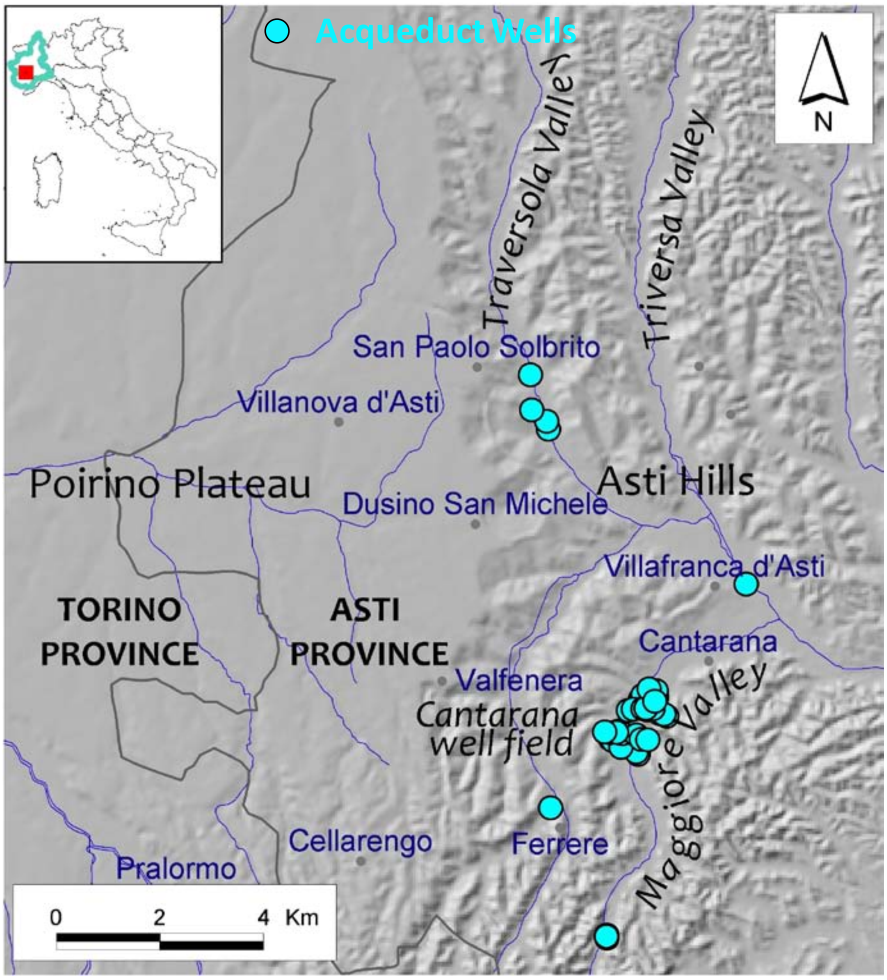

Figure 1 - The well fields of Maggiore and Traversola Valleys. The location of drinking water wells is represented by cyano circles; in the inset a wider scale location of the area is reported.

Groundwater in the area is in the overall characterized by good quality and is generally well protected by anthropogenic contamination. Nevertheless the shortage of oxygen in depth favors the dissolution of manganese from the aquifer matrix. For this reason, a treatment process is adopted to keep the concentration of manganese within the law limits.

The exploited confined aquifer consists of Pliocene marine deposits (mainly "Asti Sands" formation). This aquifer has been intensively exploited since the early XX century. Groundwater exploitation has been consistently increasing in time: at the beginning of the century the withdrawal corresponded only to some l/s and then it gradually increased up to the current amount (i.e. 530 l/s). As an example, in recent years, over the period 1996 to 2009, the extraction rate increased from 13,4to 14,4 Mm^3/year (Lasagna et al. 2014).

This intense groundwater exploitation has produced undesirable consequences as subsidence, well damages and a gradual deepening of the groundwater level. Indeed, at the end of the XIX century, the piezometric levels of the Maggiore Valley wells were up to 10 m higher than the ground surface, creating the conditions for an artesian aquifer(Sacco 1924, Beretta et al. 1999). Since 1920 to present, a reduction of more than 50 m in groundwater level has been observed (Lasagna et al. 2014). Continuous extraction over the decades has resulted in the progressive reduction of the artesian area: at present artesian conditions prevail only in the northern sector of the aquifer (see also later Figure 3). Groundwater overexploitation is the cause of relevant land subsidence within the Maggiore Valley well field, resulting in a differential lowering of ground surface and cracking of some buildings. The lowering of groundwater level create also the need for a progressive deepening of the most recently constructed wells to access the water resource.

In order to mitigate the aquifer overexploitation, the management authorities (ATO 5 - Ambito Territoriale Ottimale n.5 Astigiano Monferrato) put in place a preparatory activity of groundwater level monitoring by means of distributed piezometers in the area. The drawdown recorded by these monitoring wells in the Maggiore Valley was of about 0.8 m for the year 2010, denoting that a steady state was not yet reached. As a consequence, a reduction of withdrawals was prescribed to aim in a stabilization of the groundwater levels. The necessary discharge for restoring the regular water supply to the population (about 100 l/s) was guaranteed by an interconnection (a 17 km long pipe) with the Monferrato aqueduct (De Luca et al. 2009). This interconnection was completed and became operative in 2012, leading to a partial rising of the piezometric level. Moreover, a groundwater flow model was implemented with four different scenarios, each with different combinations of extraction rates and distribution of extraction points (Lasagna et al. 2014). The best solution in order to mitigate the negative impact of the withdrawals consisted in the reduction of groundwater extraction to 150 l/s with a combined relocation of some wells in nearby areas (see also later in Figure 3) characterized by high piezometric levels (also artesian areas) and suitable logistic and hydrogeological conditions for well drilling.

The design of the positions of new wells require a detailed knowledge of the hydrogeological setting of these nearby areas. Indeed even if the general setting is almost well known and reported in several studies (e.g. Beretta et al. 1999; Bove et al. 2005; Vigna et al. 2010; Lasagna et al. 2014), a scarcity of lithological and hydrogeological information on a local scale has to be underlined. Particularly scarce stratigraphic information are present from the already drilled wells, most of them are dated and lack in appropriate core descriptions so that no specific information is available at the local scale. Specific surveys are therefore necessary to obtain preliminary information over wide investigation areas. This task can be profitably afforded by the use of geophysical methods, particularly electromagnetic and electrical. Electrical and electromagnetic methods are indeed considered as the most siutable geophysical methods in the field of groundwater exploration. With the recent increasing interest in water resources, several projects related to groundwater problems have been carried out using these methods for water quality monitoring, water research and exploitation (e.g. Soupios et al. 2010; Batte et al. 2008; Cimino et al. 2007; Kafri and Goldman 2005; Young et al. 2004) and different recent literature works are available to document the effectiveness of these methods with this aim (e.g. Parsekian et al., 2017; Nicaise et al., 2012; Sirhan et al. 2012; Ezersky et al., 2011). Particularly many regional case histories are available to demonstrate the utility of Time Domain Electromagnetic Methods (TDEM) for groundwater exploration. The advantage of using TDEM is related to the possibility of having a great amount of data over a wide area with relatively reduced economic effort particularly if compared to perforation costs. Changes in imaged resistivity at critical depths can be related to lithology, water saturation, and water quality variations. On a complementary side Electric Resistivity Tomography (ERT) can support the interpretation of TDEM data particularly for the near surface resistivity values and map the 2D distribution of resistivity along a specific section. The combined use of ERT and TDEM methods is generally well known in hydrogeology (Dahlin 1996; Abdul Nassir et al. 2000; Seaton and Burbery 2000; Demanet et al. 2001).

In this paper the results of geophysical investigations with the use of ERT and TDEM are therefore reported and discussed to detail the geological and hydrogeological setting of the studied area. More specifically, ERT is used to image resistivity variations along specific sections and establish a correct parameterization for TDEM inversion and a calibration for the near surface resistivity values. Then TDEM soundings are inverted with a Spatially constrained approach to obtain a quasi 3D model of the investigated areas. These results were used to locally better investigate the thickness of the aquifer, map its variation in the areas and select new exploitation points. After a general description of the hydrogeological setting of the area, geophysical surveys are presented and discussed in the aim of water well relocation.

2. Hydrogeological Setting

The geological formations within the area are grouped in six hydrogeological complexes (Figure 2). These complexes are distinguished on the basis of grain size and permeability of the constituting deposits (Bortolami et al. 1978; Carraro 1996; Bove et al. 2005; Debernardi et al. 2008; De Luca et al. 2014; Lasagna et al. 2016).

The Pre-Pliocene marine complex (Eocene–Miocene) consists of silty-clayey pre-Pliocene sediments (Conglomerates of Cassano Spinola, Gessoso-Solfifera Formation, Marls of St. Agata Fossili) with very low or negligible permeability. The Pliocene marine complex (Lower-Middle Pliocene) is represented by the Lugagnano Clay and the Asti Sands. The Lugagnano Clay consists of sandy-marly clays, intercalated with coarser sediments in the uppermost part. They have a very low or negligible permeability and represent an aquiclude, under the overlying Asti Sands. On the contrary, the Asti Sands are sandy sediments, alternated with lenses of fine sand, sandy-gravel, clayey sand, silty-sandy and silty-clayey levels with very low permeability. The alternation between mainly sandy sediments with a good permeability and poorly permeable levels makes this complex a multi-layered aquifer system, in which the various aquifer levels can intercommunicate through semi-permeable levels. This hydrogeological unit is currently exploited by the well fields of Maggiore and Traversola Valleys. Artesian phenomena occur in the Traversola, Triversa and Stanavasso Valleys and (to a lesser extent) in the Maggiore Valley between the towns of Villafranca d'Asti and Cantarana (see also later in Figure 3). The Pliocene Sandy Complex reaches a thickness ranging between 150 and 200 m at Maggiore Valley while eastward and southward it progressively becomes less thick. Conversely it thickens under the Poirino Plateau (westward), where it deepens sharply below the overlying Villafranchian Complex. In correspondence of Maggiore Valley well field the average value of hydraulic conductivity in Asti sands is 3.10^{-4} m/s, according to previous pumping tests (Ajassa et al. 2011).

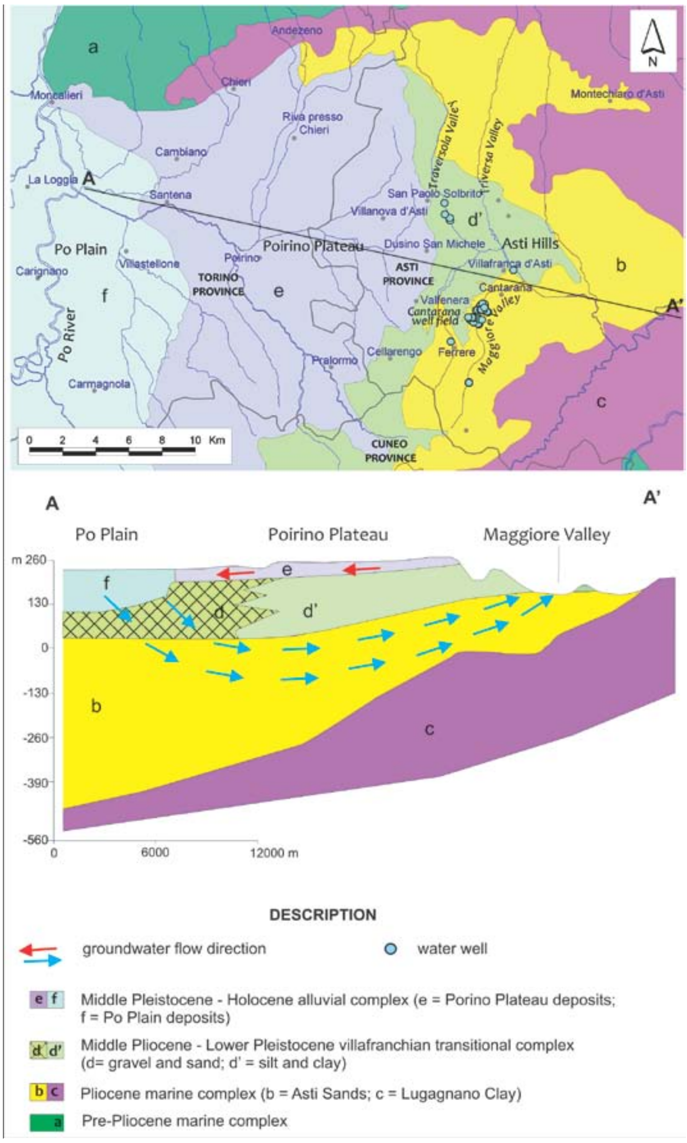

Figure 2 - Map and schematic cross section of the hydrogeological complexes. The aquifer exploited by the well fields of Maggiore and Traversola Valleys is represented by the Pliocene marine sandy Complex.

The Villafranchian transitional complex (Middle Pliocene-Lower Pleistocene) consists of an alternation of silty-clayey layers of very low or low permeability alternated with sandy and gravelly permeable levels (Boano and Forno, 1996). It almost continuously covers the Pliocene Sandy Complex even if in the Maggiore Valley it is highly eroded and locally absent. The Villafranchian complex reaches its maximum thickness (approximately 200 m) at the central part of the Poirino Plateau whileit thins northward, in contact with the Hill of Turin. In correspondence of the Poirino Plateau it contains a number of coarse-grained levels representing confined aquifers; the thickness of these layers and their continuity increase from east to west towards the Po River, at detriment of fine levels. In the studied hilly area, when present, the Villafranchian Complex mainly consists of silty-clayey sediments with rare and limited interbedded sand and sandy gravel. The prevalence of fine sediments at very low permeability as well as the reduced distribution and lateral continuity of the sandy-gravelly bodies make the Villafranchian Complex less productive in this sector.

The Alluvial Complex (Middle Pleistocene-Holocene) includes the post-Villafranchian terraced fluvial deposits of the top of the Poirino Plateau and Turin-Cuneo Plain deposits. The Poirino Plateau is characterized by silty or silty clayey, sandy and gravelly bodies, locally superimposed, overall having a thickness between 10 and 30 m. The gravelly-sandy deposits of Turin-Cuneo plain constitute an unconfined, locally semiconfined, aquifer with a high permeability and in direct connection with the hydrologic network. The highest thickness is reached along the Po River and it results variable as a function of the Pliocene or Villafranchian substrate conformation.

A piezometric map of the deep aquifers, exploited by the well fields of Maggiore and Traversola Valleys, is shown in Figure 3. It is referred to the period April-June 2013. The piezometric measurements were performed in 25 points: 22 irrigation wells, 12 of which artesians (red dots in Figure 3), and 3 piezometers. In the eastern area with respect to the Poirino Plateau, the wells are drilled in the Pliocene marine complex. In the Poirino plateau, close to its escarpment, the wells are drilled in coarse layers of the Villafranchian complex. Moving westward, the sandy Pliocene marine complex deepens rapidly, so it is no longer reached by the perforations. The piezometric map was created using the Surfer 9 software (Golden Software, Golden, CO, USA). Data were interpolated using the Kriging interpolation algorithm. The piezometric levels range between 230 m a.s.l. in correspondence to the Poirino Plateau and 142 m a.s.l. in Maggiore Valley well field. The piezometric levels generally decrease from West to East, where the piezometric surface forms a pronounced depression cone. The depth of the water table ranges between +5.60 m above ground level, in the artesian area (blue in Figure 3), and -65.20 m below ground level, East of Riva near the city of Chieri.

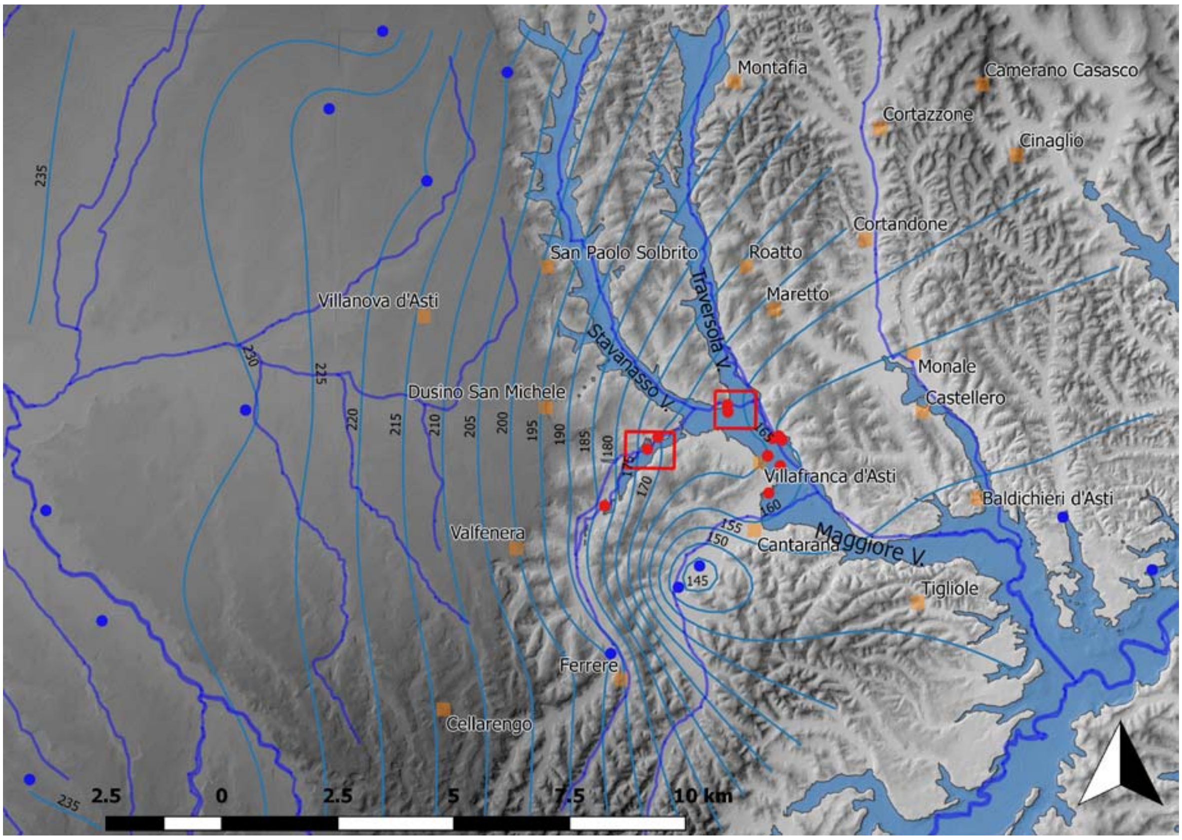

Figure 3 - Piezometric surface of the aquifer exploited by the well fields of Maggiore and Traversola Valleys,(April-June 2013) with evidence of: measuring points for piezometric map reconstruction (blue and red dots; particularly red dots are referred to artesian wells), the supposed artesian area (in blue) and the potential relocation zones (red squares).

The resulting main groundwater flow direction of Pliocene marine aquifer is from West to East. According to the flow lines direction, the regional recharge of the aquifer is guaranteed by the Turin and Cuneo plains. This flow is opposite to the groundwater flow direction in the shallowest aquifer (Figure 2) (Bove et al. 2005). The hydraulic gradient of the deep acquifer varies from values between 1-5 ‰ in the western sector (Poirino Plateau), to 1-10% in the depression cone of Maggiore Valley. The strong exploitation of the aquifer has lead to a remarkable, and localized, decrease in the piezometric level around the most exploited area (Figure 3). Therefore the need for relocation of the extracting wells. The potentially suitable areas for the wells relocation have been identified within the artesian area situated North and West of Maggiore Valley. The management authority has preliminary identified two areas that are the most suitable from a logistical point of view (proximity to existing pipes, expansion capabilities, possibility of building a new treatment plant for precipitating manganese from groundwater, etc.). An area is located in the municipality of Villafranca d'Asti, the other in the territory of Dusino San Michele (Figure 3). In these areas, geophysical surveys have been conducted in order to better investigate, at a local scale, the thickness and productivity of the aquifer.

3. Material and Methods

TDEM and ERT methods are well known in exploration geophysics. Both methods measure the same fundamental property, electrical conductivity (or its inverse, resistivity), with different degrees of sensitivity.

ERT involves the injection of an electrical current into the ground by means of electrodes (galvanic contact) and in measuring the resulting voltage at several points. Electrical resistivity is the ratio of the observed electrical voltage versus the injected current, taking into account a geometric factor, which depends on the mutual distance between the electrodes (Reynolds, 2011). An inversion procedure of several collected data, according to a tomographic approach, allows to get a 2D distribution of the resistivities along a vertical section of the subsoil. In the study area, this method was adopted for a first draft imaging of the resistivity distribution along a single section cutting almost the entire investigation areas and for establishing a proper layer parameterization for the TDEM inversion.

The main advantage of TDEM with respect to ERT is that the method does not require the galvanic contact between transmitter and receivers and the ground. TDEM is based on the propagation of an induced electromagnetic field; a steady current is forced to flow through a loop for some milliseconds to allow a turn-on transient in the ground to dissipate. The transient of the secondary field is a function of the distribution of the electrical conductivity in the subsoil. A receiver loop is used to detect the transient field;

the electrical resistivity is then estimated by analyzing the transient decay of the secondary field (e.g. McNeill, 1990). The result of TDEM data is therefore a 1D resistivity profile under the receiver position. The investigated volume by TDEM is a function of the descending and expanding image of the transmitted current; usually TDEM allows for deeper investigation than ERT if a reliable quality of the received signal is attained. The method is sensitive mainly to conductive formations therefore it has been used to aerially extend the evidences of ERT with respect to the bottom of the acquifer (Pliocene Silty-clayey Complex). With the aim of relating the information among different 1D TDEM profiles the imaging of the subsoil can be based according to the laterally constrained inversions techniques (Auken and Christensen, 2004). This approach allows to invert simultaneously all the 1D soundings aligned along some profiles taking into account the spatial dependency of the model parameters. The original lateral constrained method has been extended by considering a spatially constrained inversion to process a data set of different soundings located in a regular or not regular grid on the surface; this approach has been already applied to TDEM data (e.g. Viezzoli et al., 2008) and to several other type of geophysical data (e.g. Socco et al., 2009; Comina et al., 2012). This extends the capability of the lateral constrained inversion to a pseudo 3D mapping of the subsurface.

3.1 Surveys locations and data acquisition

Locations of the surveys in the two investigated areas are reported in Figures 4 and 5. For ERT two surveys were acquired, one in the Dusino San Michele area (along WSW - ENE direction) and the other in the Villafranca area (along NNW - SSE direction). Both lines are 940 m long, with 48 electrodes with spacing of 20 m. A total of 871 resistance data for each line were acquired using a Wenner-Schlumberger quadripole configuration. An IRIS Syscal Pro instrument with external power was used for data acquisition. Each voltage data is a stack of 4 measurements (each 500 ms long). For TDEM, 20 soundings were collected both in the Dusino San Michele area and in the Villafranca area. A transmitter coil with size 100x100 m has been adopted in most cases, while in particular terrain conditions a 40x40 m one was adopted. Both 0.6 x 0.6 m (20 turns) and 10x10 m (2 turns) receiver coils were used for each acquisition, located at the center of the transmitter coil. Each data contains 40 measuring points, from $1.2x10^{-6}$ to $8.8x10^{-3}$ s. Injected current varied between 1 to 10 A, and a stacking of 2000 measurements was performed. The data acquisition was performed using an ABEM WalkTEM instrument. Great care has been adopted in the survey design in locating the soundings far away from electrical power lines . As evidenced in Figures 4 and 5 there are no particularly relevant topographic effects attended in the area. Only soundings located northwards of the Dusino San Michele area (i.e. soundings 1,2 and 6) have indeed a difference in elevation of about 5-10 m with respect to the bottom of the valley where the other soundings and the ERT section are located. Soundings in these positions may be affected by partial 3D effects due to the non perfect planar positioning of transmitter and receiver coils. This effect of tilt (transmitter non completely planar) is however very reduced on the late stage approximation according to the great difference between the transmitter loop-size with respect to the equivalent area of the receiver coil.

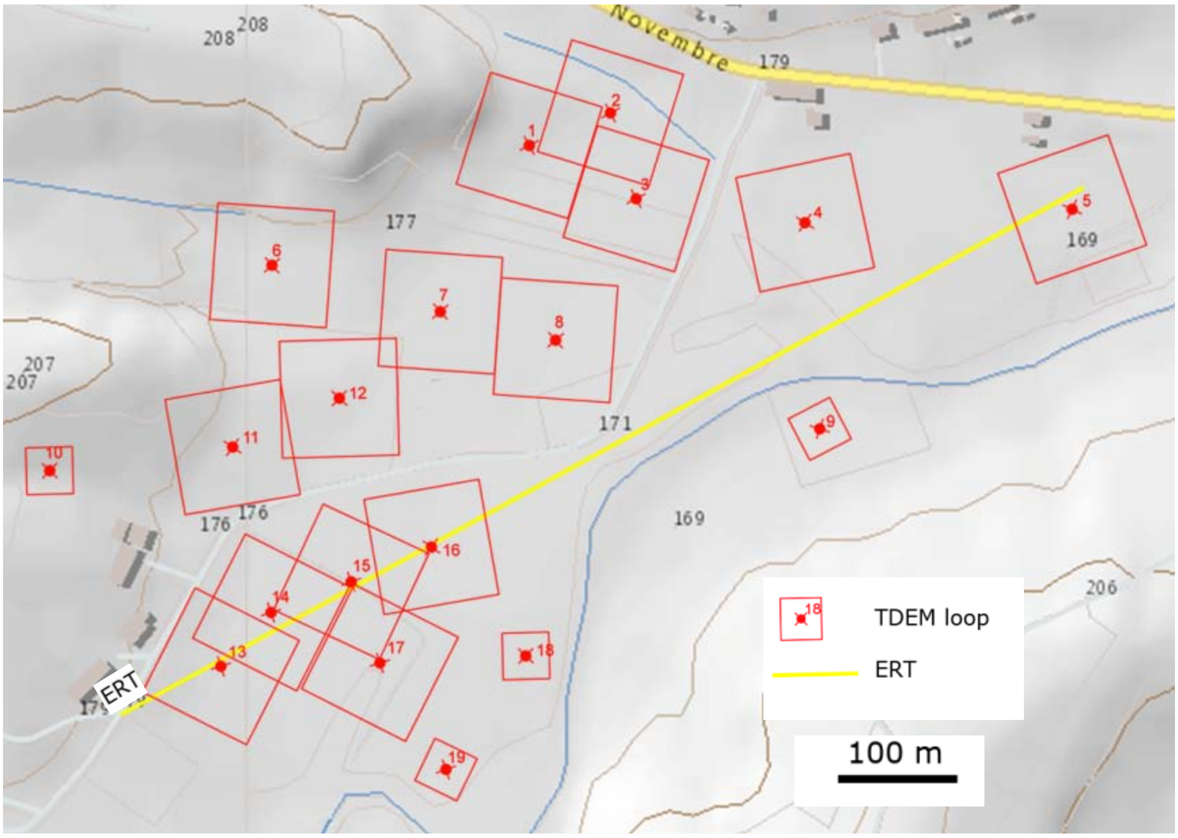

Figure 4 - Survey location in the Dusino San Michele municipality.

Figure 5 - Survey location in the Villafranca municipality.

3.2 Data processing and Inversion

ERT data were filtered in order to keep the stacked data with a variance lower than 1%, resulting in about 800 quadripoles, of the 871 acquired, for each line. The inversion process adopted is a least-square algorithm with no-constraints; commercial software Res2Dinv (Geotomo Software) has been used for data inversion.

TDEM soundings were filtered removing the outliers and the smallest times where no potential decay occurred (see also later Figure 7). Filtered data were inverted using a Spatially Constrained Inversion (SCI) method based on Matlab routines. The inversion algorithm consists of a damped least-squares inversion process in which all the TDEM soundings are inverted globally through a set of spatial constraints that tie each 1D local resistivity model to the neighboring ones to allow for an internally consistent representation of the investigated volume. In this way a unique misfit function is used. The forward problem considers a central-loop TDEM sounding for different transmitting and receiver square loop sizes, as proposed by Ingeman-Nielsen and Baumgartner (2006). They implemented electromagnetic field equations for grounded wires, frequency and transient soundings. The Hankel transforms occurring in the field equations is solved using either the Fast Hankel Transform based on digital filter theory, or a numerical integration scheme applied between the zeros of the Bessel function. The forward modeling handles complex resistivity and solutions are based on the full EM-equations as well as the quasi-static approximation.

4. Results and Discussions

Results of the inversion of the two acquired resistivity sections are reported in Figure 6. The final root mean square error (rms) obtained was of 1.39% for the Dusino San Michele site and 1.93% for the Villafranca site. An increase in resistivity below about 50 - 60 m depth from ground level is observed in both sites. This resistivity increase appears more continuous (laterally) in the Villafranca site than in the Dusino San Michele one. In the Villafranca site a deep resistivity reduction is also observed below about 140 m depth; in Dusino site a marked lateral variability is observed and a clear bottom layer cannot be depicted at depth.

Given the general geology of the area, the highlighted resistivity ranges may be interpreted as follows:

- Resistivity values between 10 and 50 Ω*m may reflect mainly the presence of fine grained formations (clay and silt), ascribable to the less permeable levels of the Asti Sands complex or to silty-clayey sediments of the Villafranchian Complex (on top of each section) and to the Lugagnano Clay constituting the bedrock in the area (at the bottom of the Villafranca section where this formation clearly emerges);
- Resistivity values between 50 and 100 Ω*m are associated to transitional formations;
- Resistivities values between 100 and 150 Ω*m, may reflect the presence of coarse grained formations (sand and gravel) mainly ascribable to the more permeable levels of the Asti Sands.

The main objective of the surveys is to detect the spatial continuity and thickness of these last more permeable levels, as precisely as possible. A layer parameterization for TDEM soundings has been preliminary established following the subdivision in these three units. However, given the wide electrode spacing adopted for the acquisition of ERT data, the two sections smear the presence of thin intercalations particularly in the near surface. Therefore, a three-layer parameterization can be too simplified for a reliable inversion of TDEM soundings; this has been indeed confirmed by the poor data fitting obtained with this inversion approach. The final adopted model is therefore based on a five-layer parameterization. The first three layers are intended to evidence possible thin intercalations in the upper formation (i.e. Asti Sands or Villafranchian complexes) while the fourth layer is the aquifer layer and the fifth the Lugagnano Clay bedrock. A variance of 50 Ωm for electrical resistivity lateral constraints and 7 m for thickness lateral constraints have been adopted in the spatially constrained inversion of the dataset.

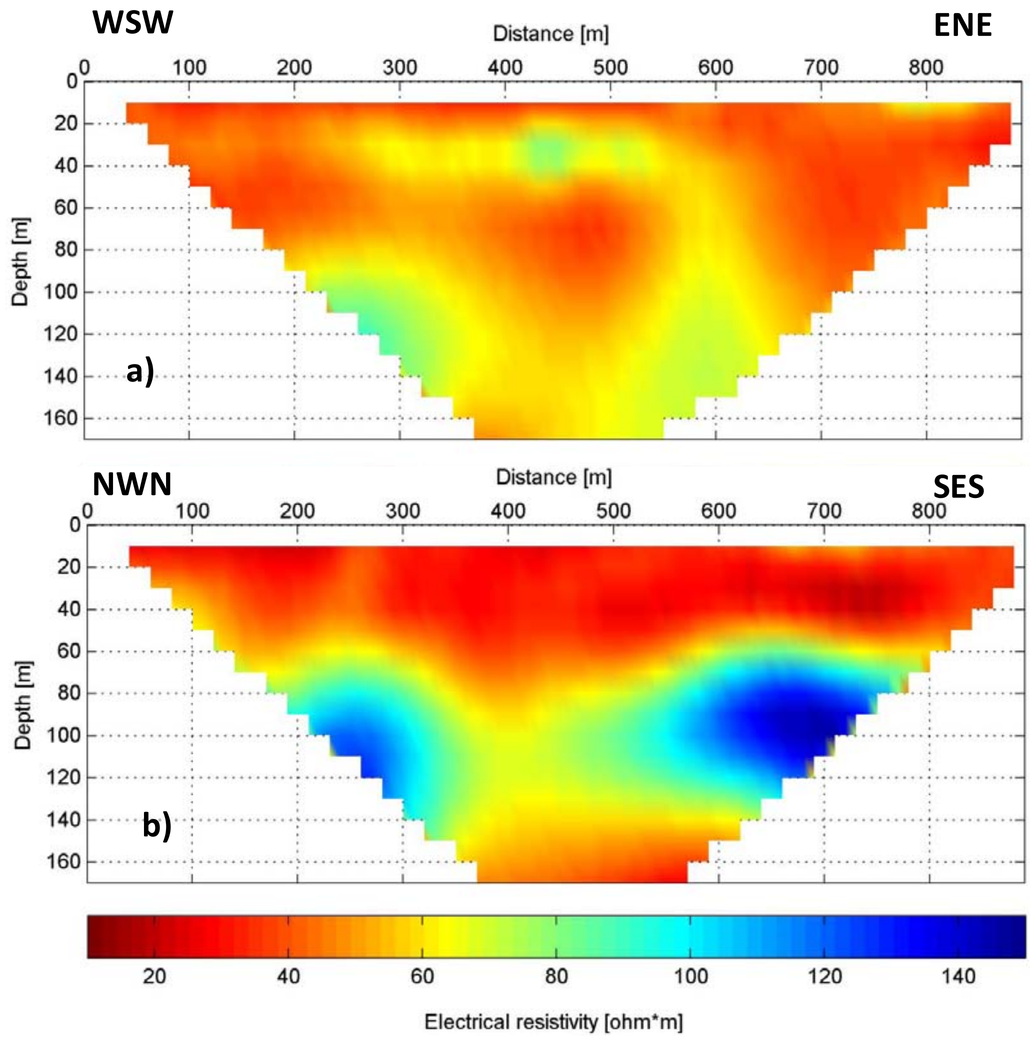

Figure 6 - ERT results: a) Dusino San Michele area and b) Villafranca area.

Examples of data acquired with the TDEM soundings in the two areas are reported in Figure 7 (red dots) with evidence of experimental uncertainty. In the Dusino San Michele area the difference between the acquired decaying curves is higher (two main clusters can be potentially identified) indicating the presence of a more variable stratigraphic sequence in the area.

The final data fitting for the two sites are also plotted in Figure 7 (blue lines) while the result of the TDEM inversion, superimposed to the two resistivity sections, are reported in Figure 8. As a whole the final rms obtained was of $4.8*10^{-4}$ V/A for the Dusino San Michele site and $1.5*10^{-3}$ V/A for the Villafranca site. Even if some of the TDEM soundings are not located perfectly along the same line of the ERT section (see Figures 4 and 5), a good match between the tomography and the TDEM results in both sections can be observed. TDEM soundings confirm the presence and lateral continuity of a higher resistivity layer at the depth from about 50 to 140 m in the Villafranca area and also depict a more articulated subsurface structure in the Dusino San Michele Area. In the upper portion of the Villafranca section higher resistive levels are also noted. These last can be attributed to locally more sandy levels within the multi-layered aquifer system of Asti Sands or to sandy-gravelly bodies of the Villafranchian Complex. Generally TDEM soundings, given their intrinsic sensitivity, tend to highlight vertical contrasts between formations, so that the supposed aquifer result more laterally uniform and with average higher resistivity values compared to the results of ERT.

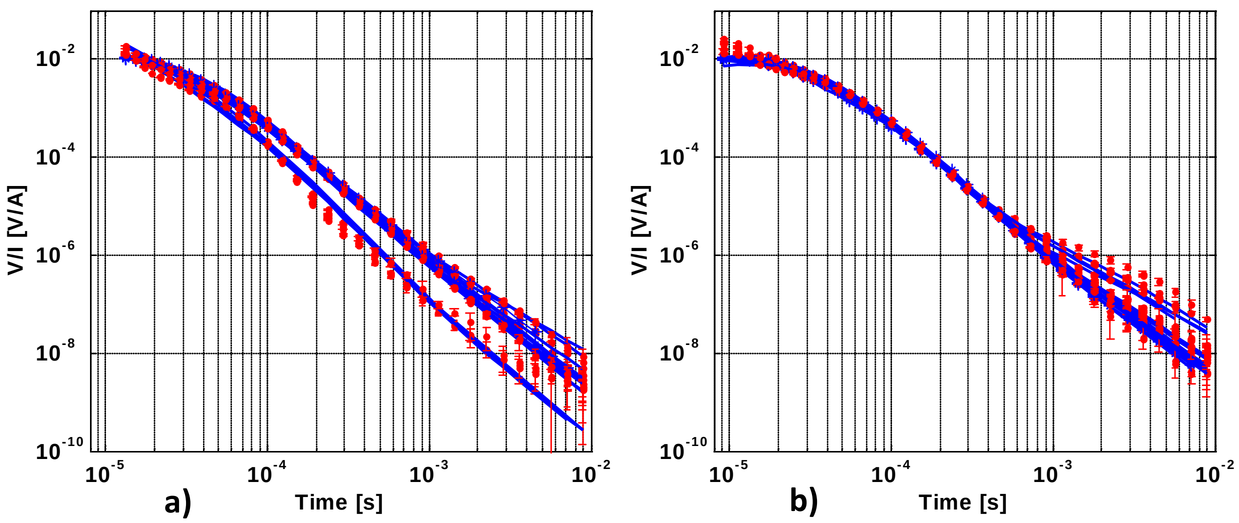

Figure 7- Curve fitting (blue lines) of TDEM soundings data (red dots with experimental uncertainty): a) Dusino San Michele area and b) Villafranca area.

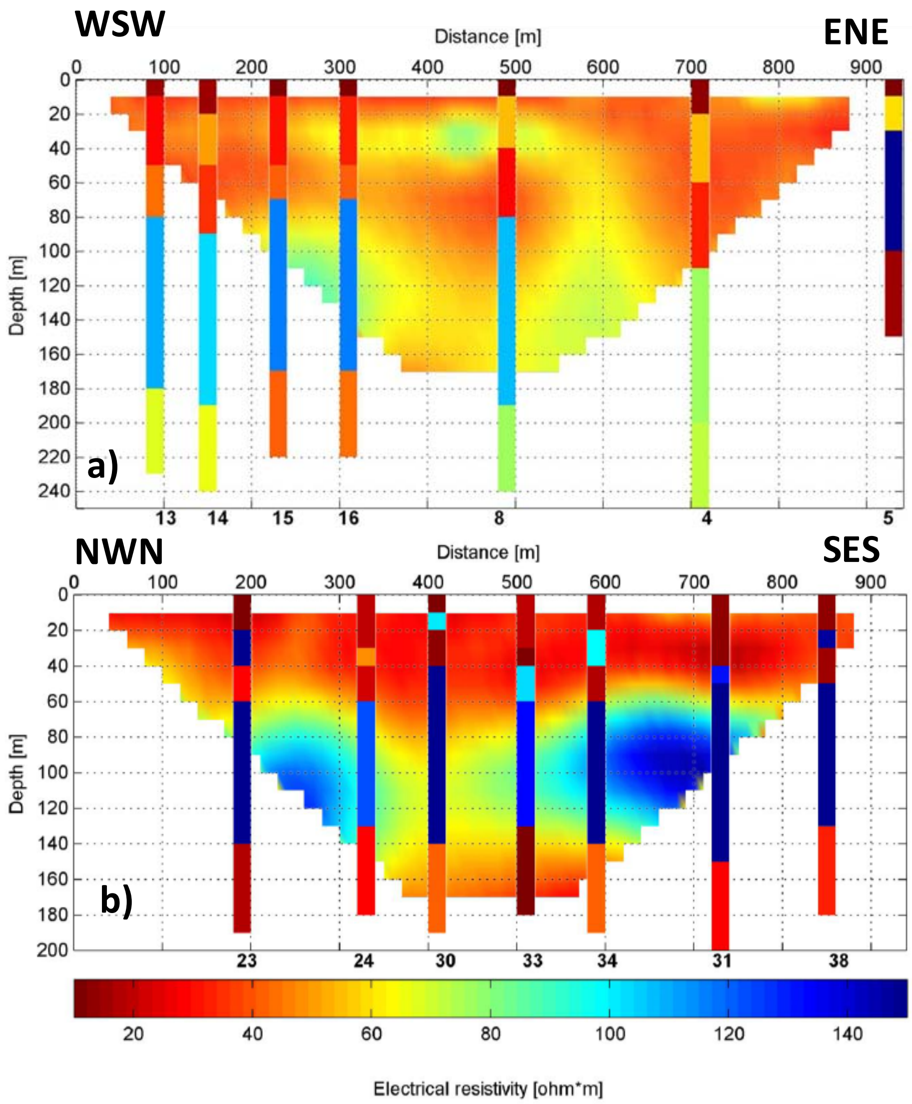

Figure 8 - Results of the TDEM inversions for the soundings nearest to the resistivity section (sounding number indicated at the bottom of each column) superimposed to the ERT results: a) Dusino San Michele area and b) Villafranca area.

In Figure 9 and 10 a 3D representation of all the TDEM soundings for the two areas are reported. The lateral continuity and general uniformity of aquifer is confirmed in the Villafranca area within the whole extension of the investigated area (Figure 10). In all the soundings an uniform aquifer layer with resistivity values between 100 and 150 Ω*m is depicted. Conversely, in the Dusino San Michele area (Figure 9) the aquifer layer result less continuous among different soundings both in terms of resistivity values and of thickness. It must be underlined that, as highlighted in the ERT interpretation, in the Dusino San Michele area the lower conductive boundary, related to the presence of the bedrock, is generally less evident and less continuous; its individuation can be therefore critical in some portions. In the same area reduced topographic effect could be present and may have influenced the 1D TDEM interpretation of the soundings in the north of the area with the adopted forward modeling scheme. lateral effect of the rugged topography or due to the presence of 2D and 3D features close to the soundings is however limited because those effects have reduced impact on the observed vertical component of the induced electromagnetic field at the receiver.

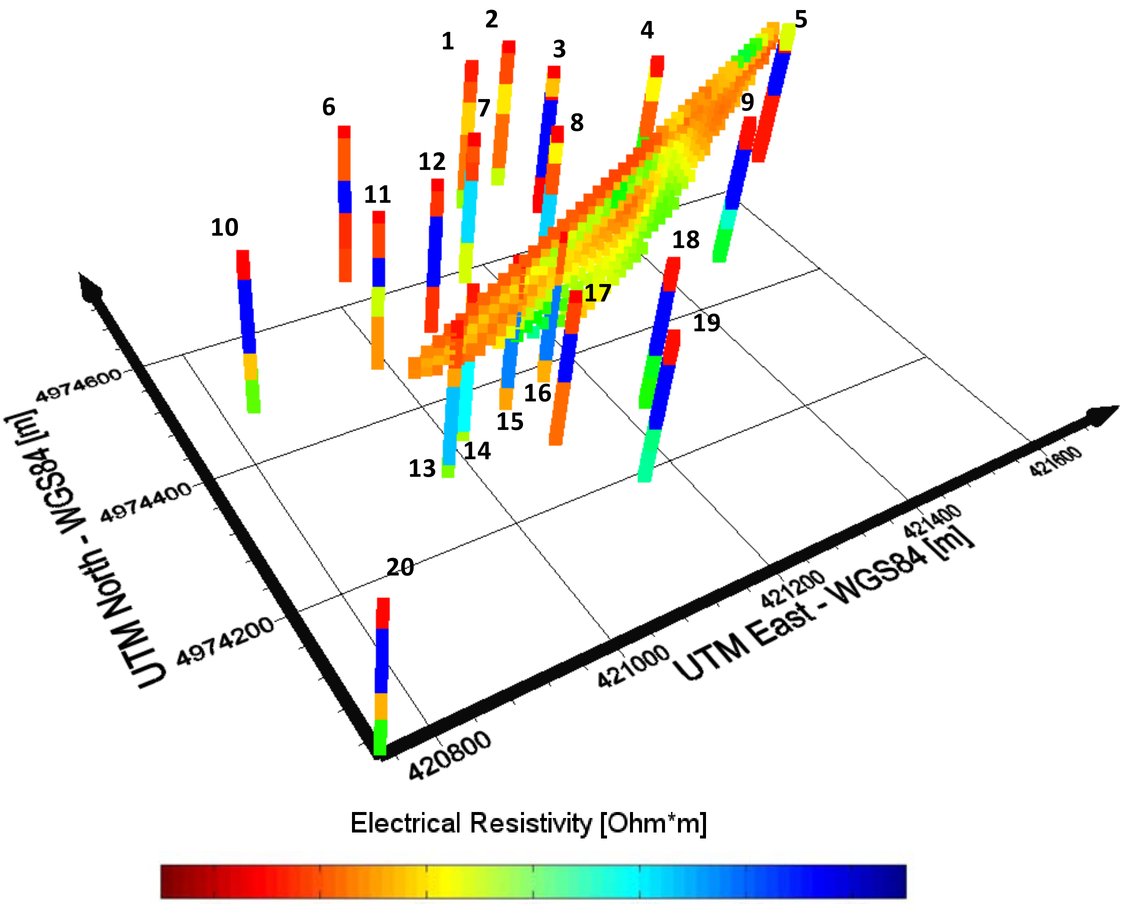

Figure 9 - 3D representation of all the TDEM soundings in the Dusino San Michele area.

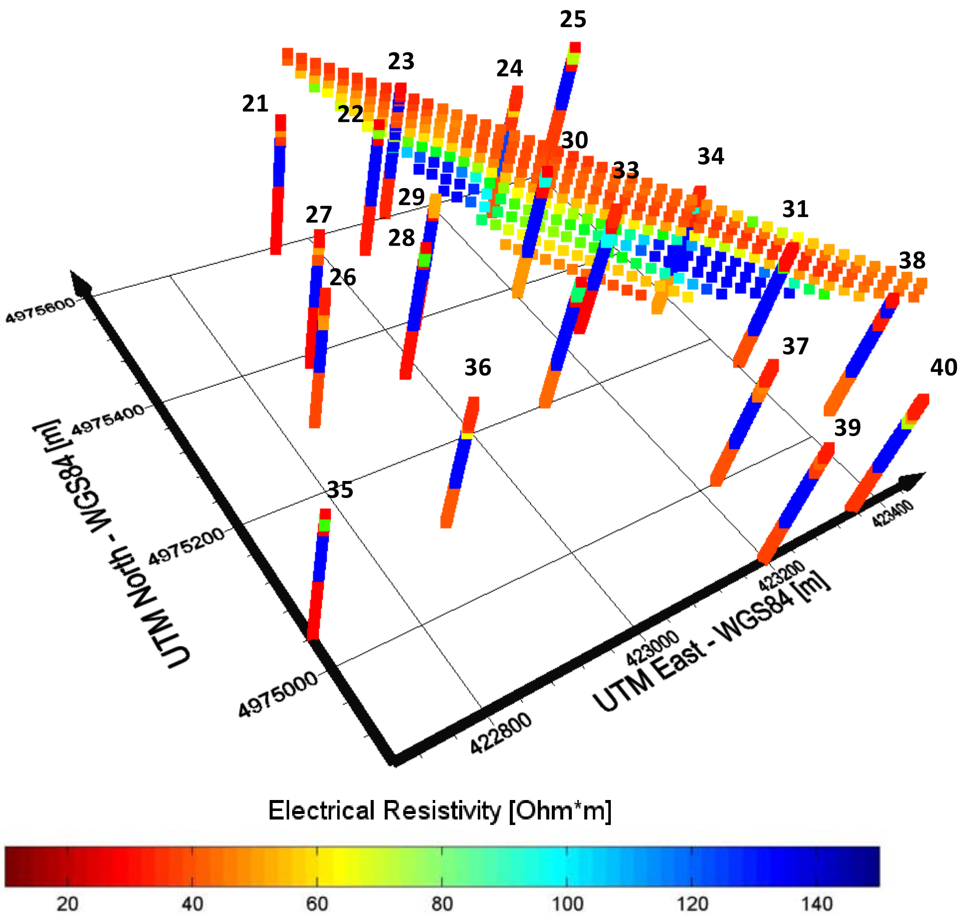

Figure 10 - 3D representation of all the TDEM soundings in the Villafranca area.

TDEM data allowed to extend the local information obtained from ERT data and to image the thickness of the resistive layer, identified as the aquifer formation, all over the investigated areas. These results are reported for the two areas in Figure 11. The thickness and the lateral continuity of the identified aquifers are reported also in Table 1. These data rely mainly on TDEM results which have been however calibrated on the ERT sections. In general the maximum thickness of the aquifer was observed in Dusino San Michele area (about 110 m); in the same area the lowest minimum thickness was also identified (nearly 0 m). In the Villafranca area a higher average thickness of the aquifer was identified (81 m). This is due to a more continuous distribution of the aquifer in Villafranca with respect to Dusino San Michele area.

The aquifer formation (i.e. Asti Sands formation) in the two areas is supposed to have similar characteristics in terms of porosity and permeability. This can be confirmed also by the similar resistivity values imaged at the aquifer level in the two areas. Also, the same recharge areas are attended in the two sites. Therefore the increased average thickness and uniformity of the aquifer formation in Villafranca allow to hypothesize an increased water resource quantity and therefore most favorable conditions for drilling new wells. The slight difference that can be noted in the hydraulic gradient in the two areas (i.e. lower in Villafranca with respect to Dusino, see Figure 3) partially contrast with this hypothesis that has to be therefore confirmed by direct perforations and specific tests.

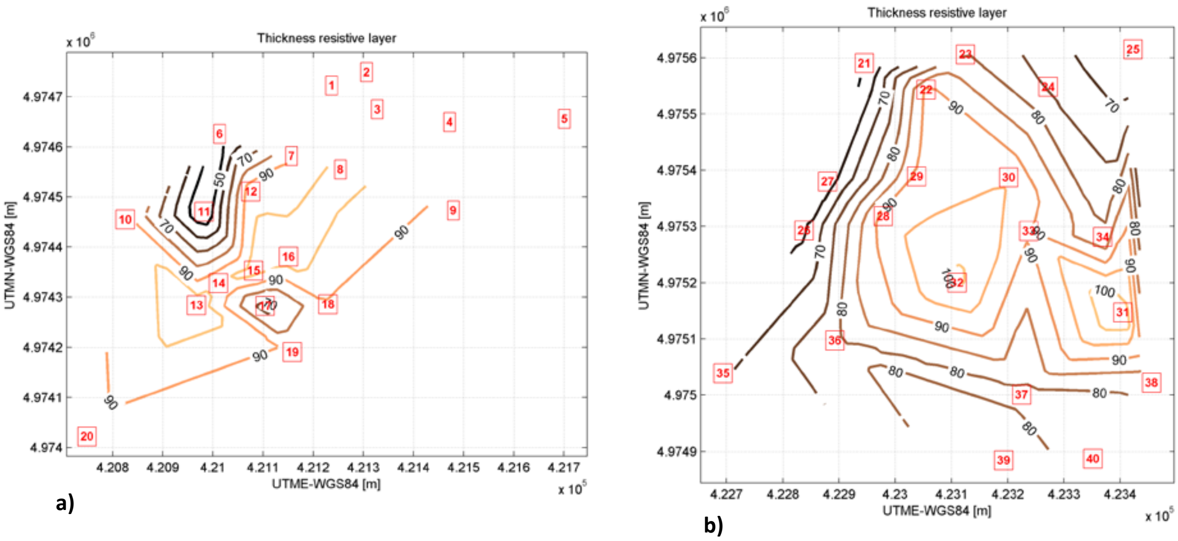

Figure 11 - Maps of the thickness of resistive layer, identified as the aquifer formation: a) Dusino San Michele area and b) Villafranca area.

Table 1 - The thickness and the lateral continuity of the resistive layer, identified as the aquifer formation, in the studied areas.

Resistive layer (aquifer)	**Dusino San Michele area**	**Villafranca area**
average thickness (m)	73.8	81
maximum thickness (m)	112	106
minimum thickness (m)	0	64
layer continuity	discontinuous	continuous

The most favorable condition of the Villafranca area are also confirmed by independent data, particularly from the observed electrical conductivity of groundwater in nearby wells reported in Table 2. As it can be noted, the water EC at Villafranca appears generally uniform confirming the hypothesis of a laterally interconnected aquifer. Given the average water conductivity in Villafranca area a formation porosity can be estimated on the basis of the Archie's (1942) law. This formula, which is valid for saturated formations under the assumption of infinitely resistive grains, relates the measured formation resistivity to the water resistivity and porosity by means of appropriate calibration factors:

$$\rho_F = a\frac{\rho_w}{\varphi^m} \quad (1)$$

where ρ_F is the measured formation resistivity, ρ_w is the water resistivity, φ is the porosity, *a* and *m* are two coefficients related respectively to tortuosity (*a*) and cementation (*m*) of solid skeleton. Formation porosity can be determined from equation 1 with the appropriate and site dependent calibration factors (*a* and *m*). There are several proposed ranges in literature for these parameters for materials similar to the ones of this study (e.g. Winsauer et al., 1952; Tixier et al., 1968; Carothers, 1968; Porter and Carothers, 1970). Lower values of m-parameter refer to cemented material or spherical shaped grains, while higher values means a less cemented material or where mineral grain flattening or elongation are relevant. Since no detailed information on the grain size distribution of the formations is available a rough estimate of the expected porosity values can be achieved by selecting the *a* and *m* parameters varying in wide ranges (0.6 – 1.4 for the *a* parameter and 1.1 – 1.7 for the *m* parameter respectively). The water resistivity values have been estimated according to the available well log data, while formation resistivity has been chosen from the results of our geophysical investigations in the range 120 - 150 Ω*m. The lower resistivity bound has been limited to 120 Ω*m in order to exclude layers more rich in clays and/or fines within the Asti sand formation. The resulting porosity ranges refer therefore to the most permeable levels of the Asti Sands formation. Evaluated porosity values (Table 2) are fairly constant in the area unless the high approximation in the calibrating factors and formation resistivity. Given these porosity values a medium-high productivity of the aquifer can be therefore again assumed in the area.

Table 2 - Water conductivity from wells in the Villafranca area and resulting formation porosity.

Well	Electrical conductivity [µS/cm]	Porosity [-]
VLF513	393	0.28 ± 0.12
VLL563	376	0.29 ± 0.13
VLL570	458	0.26 ± 0.12
VLL577	340	0.32 ± 0.13
P1BIS	419	0.27 ± 0.12
SP4	369	0.30 ± 0.13

5. Conclusions

Geophysical surveys performed within this study allowed to depict the depth and lateral continuity of the supposed aquifer level in the two examined areas. The aquifer formations showed higher resistivity values, typical of sand and gravel deposits, with respect to more clayey and less permeable formations.

Combined use of ERT sections and TDEM soundings, inverted with a Spatially Constrained approach, allowed to extend the information on wider investigation areas obtaining a pseudo 3D representation of the subsurface.

In Villafranca area the aquifer formation has been observed to be more laterally continuous, whereas in Dusino San Michele area it is discontinuous, laterally less extended and locally missing. Thus even if both of studied areas show a possible aquifer layer, on the basis of geophysical surveys, the Villafranca area appears preferable for the execution of a new drinking-water well. A preliminary estimate of the porosity of the aquifer has been proposed, according to the estimated resistivity values of formation and well log data.

On the basis of the presented surveys the management authority decided to use the Villafranca area for future relocation of a water well. A pilot well will be drilled in this area in order to verify the hydrogeological characteristics and the productivity of the aquifer identified by the described geophysical surveys.

Acknowledgments

Authors are indebted with the management authorities (ATO 5 - Ambito Territoriale Ottimale n.5 Astigiano Monferrato) for funding the surveys object of this work.

References

Abdul Nassir SS, Loke MH, Lee CH, Nawawi MNM (2000) Saltwater intrusion mapping by geoelectrical imaging surveys. Geophys Prospect 48:647–661

Ajassa R., Bove A., Castellaro M., Caviglia C., De Luca D. A., Destefanis E., Forno M. G., Gregorio L., Lasagna M., Masciocco L. (2011). Convenzione tra il Dipartimento di Scienze della Terra dell’Università degli Studi di Torino e l’Autorità d’Ambito n°5 Astigiano Monferrato “Aggiornamento ed approfondimento dello studio delle falde idriche sotterranee di Valle Maggiore (di Cantarana) e di Valle Traversola (San Paolo Solbrito) per la razionalizzazione dei prelievi idropotabili e per la definizione delle aree di salvaguardia”. unpublished report.

Archie, G. E. (1942). "The electrical resistivity log as an aid in determining some reservoir characteristics." Transactions of the AIME 146(01): 54-62.

ATO5 (2015). Valutazione ambientale strategica. Rapporto ambientale. http://www.regione.piemonte.it/ambiente/valutazioni_ambientali/dwd/vas/pianoAmbito5/1_RapportoAmbientale.pdf. Accessed 03 October 2017.

Auken E., Christiansen A.V., 2004. Layered and laterally constrained 2D inversion of resistivity data. Geophysics 69: 752-761.

Batte A, Muwanga A, Sigrist PW, Owor M (2008) VES as an exploration technique to improve on the certainty of groundwater yield in the fractured crystalline basement of eastern Uganda. Hydrogeol J 16(8):1683–1693

Beretta GP, De Luca DA, Masciocco L, Novo M (1999) Conoscenza e protezione dell’acquifero plio-pleistocenico di interesse strategico dell’Astigiano occidentale e tutela del campo acquifero della valle Maggiore di Cantarana. Atti del 3_ convegno nazionale sulla protezione e gestione delle acque sotterranee per il millennio. Quaderni di geologia applicata, Pitagora Ed. Bologna

Bortolami GC, Braga G, Colombetti A, Dal Pra` A, Francani V, Francavilla F, Giuliano G, Manfredini M, Pellegrini M, Petrucci F, Pozzi R, Stefanini S (1978) Hydrogeological features of the Po Valley (Northern Italy). In: Proceedings of the IAHS conference on hydrogeology of great sedimentary basins, Budapest, Hungary, pp 304–321

Boano P., Forno MG (1996) Carta geologica dell'area-tipo della successione villafranchiana. Litografia GEDA – Torino.

Bove A, Casaccio D, Destefanis E, De Luca DA, Lasagna M, Masciocco L, Ossella L, Tonussi M (2005) Idrogeologia della pianura piemontese. Regione Piemonte Direzione Pianificazione delle Risorse Idriche, Mariogros Industrie Grafiche S.p.A., Torino, pp 17 (with CD-Rom)

Carothers, J.E., A statistical study of the formation factor relation, The Log Analyst, 1968, 9.

Carraro F (1996) Revisione del Villafranchiano nell'area-tipo di Villafranca d'Asti (The Villafranchian in the Villafranca d'Asti type-area: a revision). Il Quaternario It Journ Quatern Sc 9(1):5–120

Cimino A, Cosentino C, Oieni A, Tranchina L (2007) A geophysical and geochemical approach for seawater intrusion assessment in the Acquedolci coastal aquifer (Northern Sicily). Environ Geol 55:1473–1482

Comina, C., Socco, L.V., Manzella, A. Pseudo-3D characterization of a geothermal field through magneto telluric (2012) Near Surface Geoscience 2012,

Dahlin T (1996) 2D resistivity surveying for environmental and engineering applications. First Break 14:275–283

De Luca DA, Dell'Orto V, Forno MG,, Gregorio L, Lasagna M, Masciocco L (2009). Assetto idrogeologico della Pianura Piemontese in un'area caratterizzata dalla presenza di un sito nucleare e di un importante campo acquifero (Hydrogeological structure in Piedmont Plain in an area characterized by the presence of a nuclear site and an important aquifer field). Rend. Online Soc. Geol. It, pp. 201-202.

De Luca DA, Destefanis E, Forno MG, Lasagna M, Masciocco L (2014) The genesis and the hydrogeological features of the Turin Po Plain fontanili, typical lowland springs in Northern Italy. Bull Eng Geol Environ 73:409–427. doi:10.1007/s10064-013-0527-y

Debernardi L., De Luca D.A., Lasagna M. (2008). Correlation between nitrate concentration in groundwater and parameter affecting aquifer intrinsic vulnerability. Environ. Geol. 55: 539-558. ISSN: 0943-0105. doi: 10.1007/s00254-007-1006-1

Demanet D, Renardy F, Vanneste K, Jongmans D, Camelbeeck T, Megrahoui M (2001) The use of geophysical prospecting for imaging active faults In the Roer Graben, Belgium. Geophysics 66:78–89

Ezersky, M., Legchenko, A., Al-Zoubi, A., Levi, E., Akkawi, E., Chalikakis, K. (2011) Tem study of the geoelectrical structure and groundwater salinity of the nahal hever sinkhole site, dead sea shore, Israel Journal of Applied Geophysics, 75 (1), pp. 99-112.

Ingeman-Nielsen T, Baumgartner F (2006). CR1Dmod: A Matlab program to model 1D complex resistivity effects in electrical and electromagnetic survey. Computers & Geosciences 32: 1411-1419

Kafri U, Goldman M (2005) The use of the time domain electromagnetic method to delineate saline groundwater in granular and carbonate aquifers and to evaluate their porosity. J Appl Geophys 57:167–178

Lasagna M., Caviglia C., De Luca D. A. (2014). Simulation modeling for groundwater safety in an overexploitation situation: the Maggiore Valley context (Piedmont, Italy). Bull Eng Geol Environ (2014) 73:341–355. DOI 10.1007/s10064-013-0500-9

Lasagna M., De Luca D.A., Franchino E. (2016). Nitrate contamination of groundwater in the western Po Plain (Italy): the effects of groundwater and surface water interactions. Environ Earth Sci, 75:240. doi 10.1007/s12665-015-5039-6.

McNeill J.D. (1990). Use of electromagnetic methods for groundwater studies. In: Geotechnical and Environmental Geophysics, Editor Ward , SEG, 1: 191-218.

Nicaise Y, Descloitres M,Alassane A, Mama D and Boukari M (2012) Environmental Geophysical Study of the Groundwater Mineralization in a Plot of the Cotonou Littoral Zone (South Benin) International Journal of Geophysics, Volume 2012 (2012), Article ID 329827, 10 pages.

Parsekian, A., Grombacher, D., Davis, A., Flinchum, B., Munday, T., Cahill, K. (2017) Near-surface geophysics for informed water-management decisions in the Anangu Pitjantjatjara Yankunytjatjara (APY) lands of South Australia The Leading Edge, 33 (12), pp. 1342-1347.

Porter, C. R., & Carothers, J. E. (1970). Formation Factor-Porosity Relation Derived From Well Log Data. Society of Petrophysicists and Well-Log Analysts.

Reynolds John M. (2011) An Introduction to Applied and Environmental Geophysics, 2nd Edition, Wiley Blackwell.

Sacco F (1924) Geoidrologia dei pozzi profondi della Valle Padana. Min. LL. PP., Serv. Idr., Uff. Idr. Po, pp 180.

Seaton WJ, Burbery TJ (2000) Aquifer characterization in the Blue Ridge physiographic province using resistivity profiling and borehole geophysics: geologic analysis. J Environ Eng Geophys 5:45–58

Sirhan, A., Hamidi, M.O. (2012) Characterization by electrical and electromagnetic geophysical methods of the shallow hydrogeological system at Hebron (West Bank, Palestine) in a semi-arid zone, Comptes Rendus - Geoscience, 344 (9), pp. 449-460.

Socco, L.V., D. Boiero, S. Foti, and R. Wisén, 2010, Laterally constrained inversion of ground roll from seismic reflection records: Geophysics 74, 6, G35-G45.

Soupios P, Kouli M, Vallianatos F, Vafidis A, Stavroulakis G (2010) Estimation of aquifer hydraulic parameters from surficial geophysical methods: a case study of Keritis basin in Chania (Crete-Greece). J Hydrol (Amst) 338:122–131. doi:10.1016/j.jhydrol.2007.02.028.

Tixier, M. P., Morris, R. L., and Connell, J. G., 1968, Log evaluation of low-resistivity pay sands in the Gulf Coast: Log Analyst, v. 9, no. 6, p. 3-20.

Viezzoli A., Christiansen A.V., Auken E, Sorensen K., 2008. Quasi-3D modelling of airborne TEM data by spatially constrained inversion, Geophysics 73 , F105-F113 , dx.doi.org/10.1190/1.2895521

Vigna B, Fiorucci A, Ghielmi M (2010) Relations between stratigraphy, groundwater flow and hydrogeochemistry in Poirino Plateau and Roero areas of the Tertiary Piedmont Basin, Italy Mem Descr Carta Geol d'It. XC:267–292

Winsauer, W.O., H.M. Shearing, P.H. Masson, and M. Williams (1952). Resistivity of brine saturated sands in relation to pore geometry: AAPG Bulletin, v. 36, p. 253-277.

Young M, Macumber P, Watts D, Toqy N (2004) Electromagnetic detection of deep freshwater lenses in a hyper-arid limestone terrain. J Appl Geophys 57:43–61

.